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# *Fuel Sources for All Power Electronic Grids*

H. Alan Mantooth



September 16, 2023

**What You Need to  
Know**



- **Introduction – Carbon Free by 2050?**
- **Current State of the Energy Transition**
- **Solutions Both Large and Small**
- **What is an All Power Electronics Grid?**  
*Heck, what is power electronics?*
- **Pragmatism vs. Idealism**

- **B.S.E.E., U of A, 1985**
- **M.S.E.E., U of A, 1986**
- **Ph.D., Georgia Tech, 1990**
- **Analogy, 1990 – 98 (Principal Engineer)**
- **U of A, Dec. 1998 – present (Distinguished Professor)**
- **21<sup>st</sup> Century Research Leadership Chair**
- **Former President of IEEE Power Electronics Society**

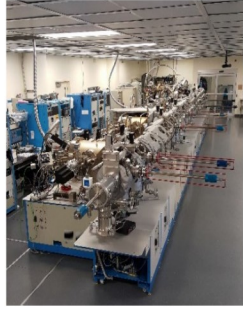




**Core Facilities**

**Federally-Funded Centers of Excellence**

**NANO**

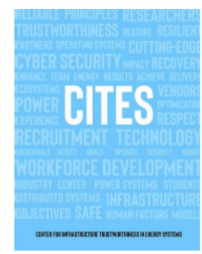
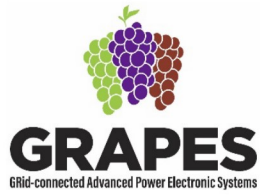
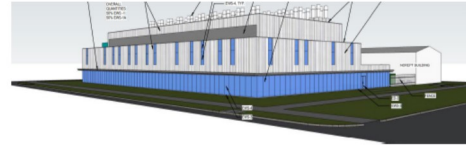


**NCREPT**



**HiDEC**

**MUSiC**



1. **Juan Balda**, *power systems and power electronics, magnetics*
2. **Zhong Chen**, *devices and fabrication*
3. **Jia Di**, *asynchronous digital IC design, cybersecurity, hardware security*
4. **Jeff Dix**, *analog & mixed-signal IC design, neural networks*
5. **Chris Farnell**, *embedded systems, cybersecurity*
6. **David Huitink**, *thermal management, packaging, and reliability*
7. **Qinghua Li**, *cybersecurity*
8. **Alan Mantooth**, *semiconductor device modeling, CAD, packaging, and power & analog IC design, cybersecurity*
9. **Roy McCann**, *power systems, motor drives, storage, cybersecurity, and controls*
10. **Yarui Peng**, *design automation tools*
11. **Greg Salamo**, *materials and devices, nitrides*
12. **Xiaoqing Song**, *power electronic packaging and conversion*
13. **Jingxian Wu**, *cybersecurity and communications*
14. **Morgan Ware**, *wide bandgap devices, capacitors*
15. **Thomas White**, *semiconductor fabrication*
16. **Yue Zhao**, *motors, machines and drives*

# What is Power Electronics?

The Energy Council: Fuel Sources for APEG



System Prototyping & Demonstrations

Control Systems

Power Electronic Circuits & Systems

Advanced Integration

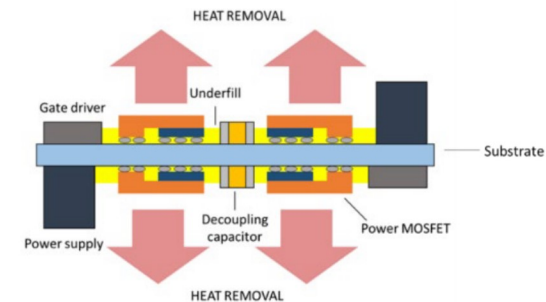
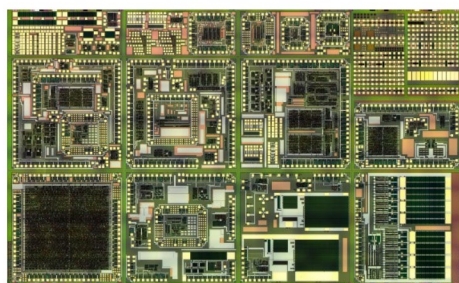
Integrated Circuits

Electronic Packaging

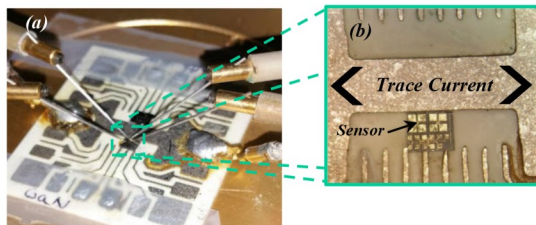
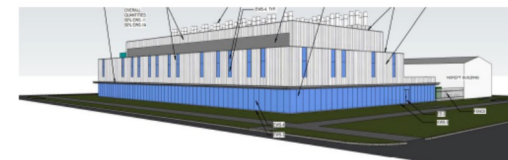
Devices

Materials

“Materials to Systems”



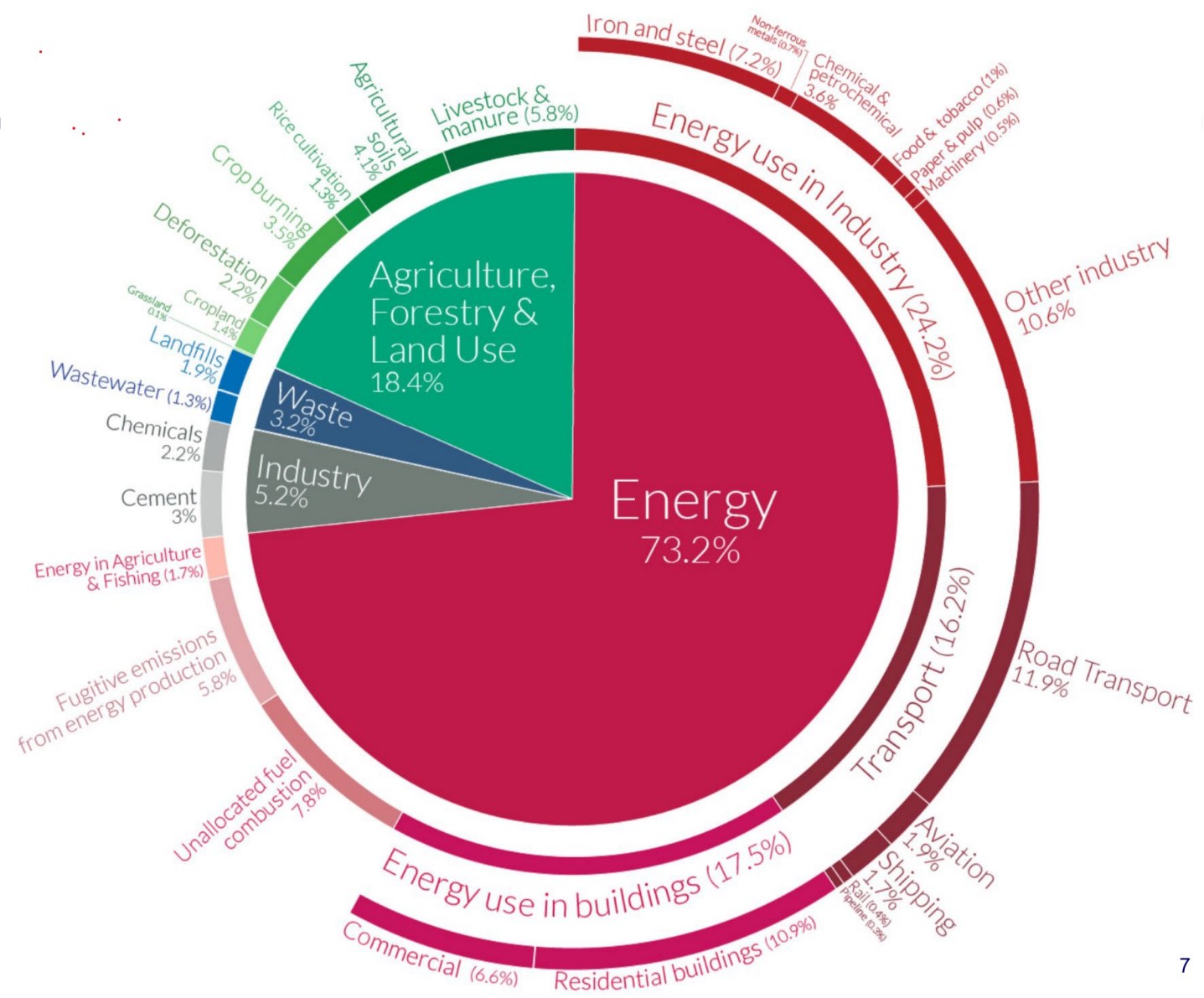
MUSiC



1. **Energy is transitioning to more electrification**
2. **Climate is changing**
3. **Can #1 help #2?**
4. **What does this mean for society in general?**

## Greenhouse Gas Emissions by Sector:

- Energy is by far the largest
- Agriculture a distant, but important second



Global greenhouse gas emissions by sector (2016)  
 Source: Climate Watch, the World Resources Institute (2020),  
<https://OurWorldinData.org/emissions-by-sector>



- **Electrification – Can be a clean winner**
- **Renewables – Supply side**
- **Efficiency – Energy delivery systems and loads**
- **Resiliency – Build it to withstand everything**
- **Reliability – Make energy available**
- **Redesign – Rethink how to tackle the grand challenge in the same timeframe as evolutionary developments occur**
- **Reconfigurability – Helps address resiliency, reliability, equity, and availability objectives**
- **Reconstruct – Build new while upgrading old; design for reuse and interoperability**

➤ **Mobility Electrification: Why now? Why solar now? \$\$**



➤ **Average car trip is 29 miles; misleading because less than 5% of trips are over 31 miles (nhts.ornl.gov/vehicle-trips) =>**

- charge time is minimal
- cost of ownership is lower
- cost parity with ICE vehicles in 4-5 years



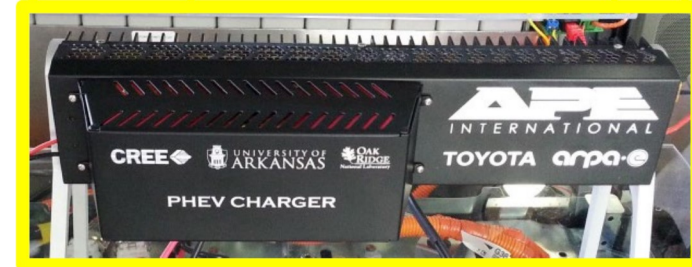
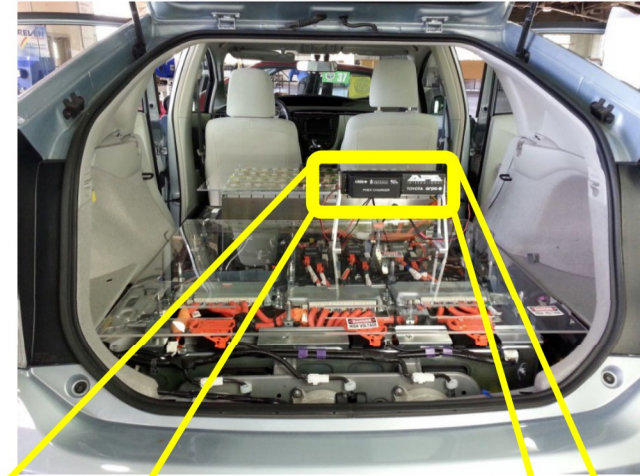
Cat says it successfully demonstrated this 793 electric mining truck at its proving ground in Arizona. Source: Caterpillar

## Key Accomplishments:

- ✓ Residential power router
- ✓ Fault diagnosis in MW-scale power converters (patent 2020)
- ✓ Battery charger electronics
- ✓ Data center electronics

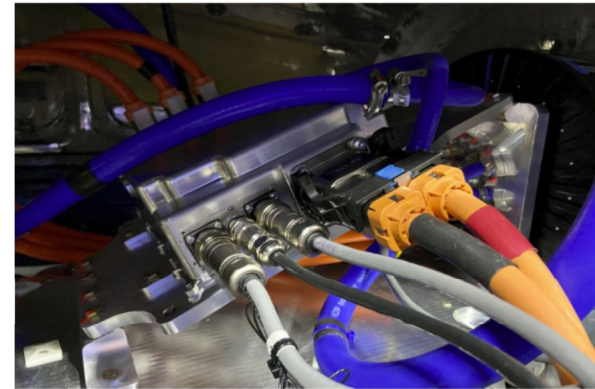
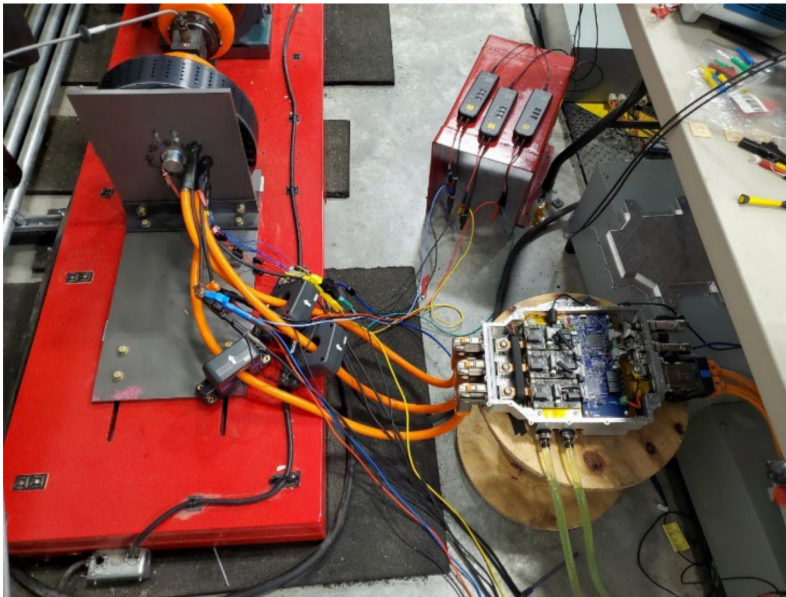
## Current Projects

- Hybrid electric Caterpillar bulldozer
- Hybrid electric aircraft
- Hydrogen-based electric aircraft
- GRAPES & POETS Centers





**Dyno Setup at UA NCREPT**

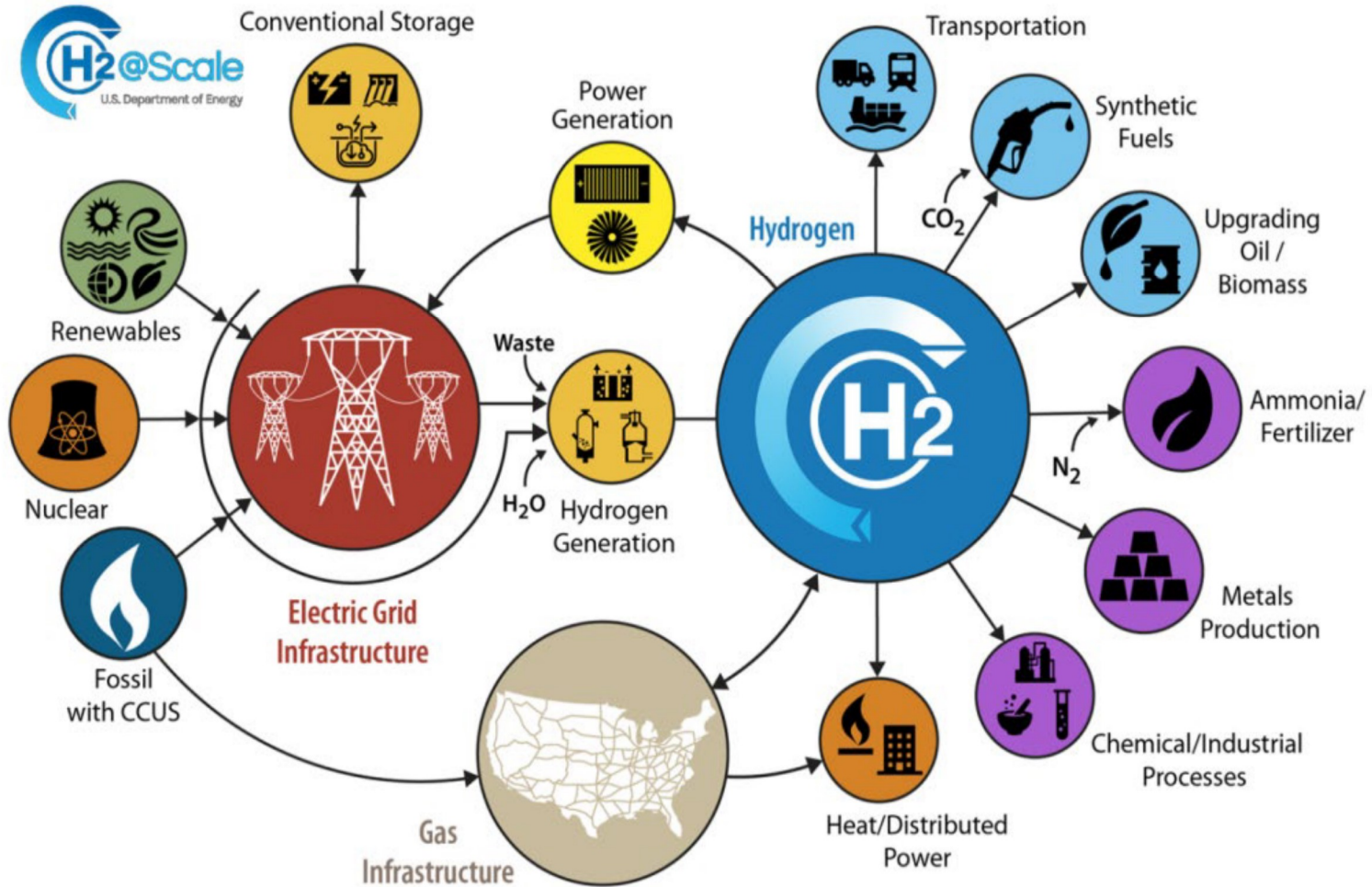


**Inverter on Ampaire Aircraft  
@ ARPA-e Summit**



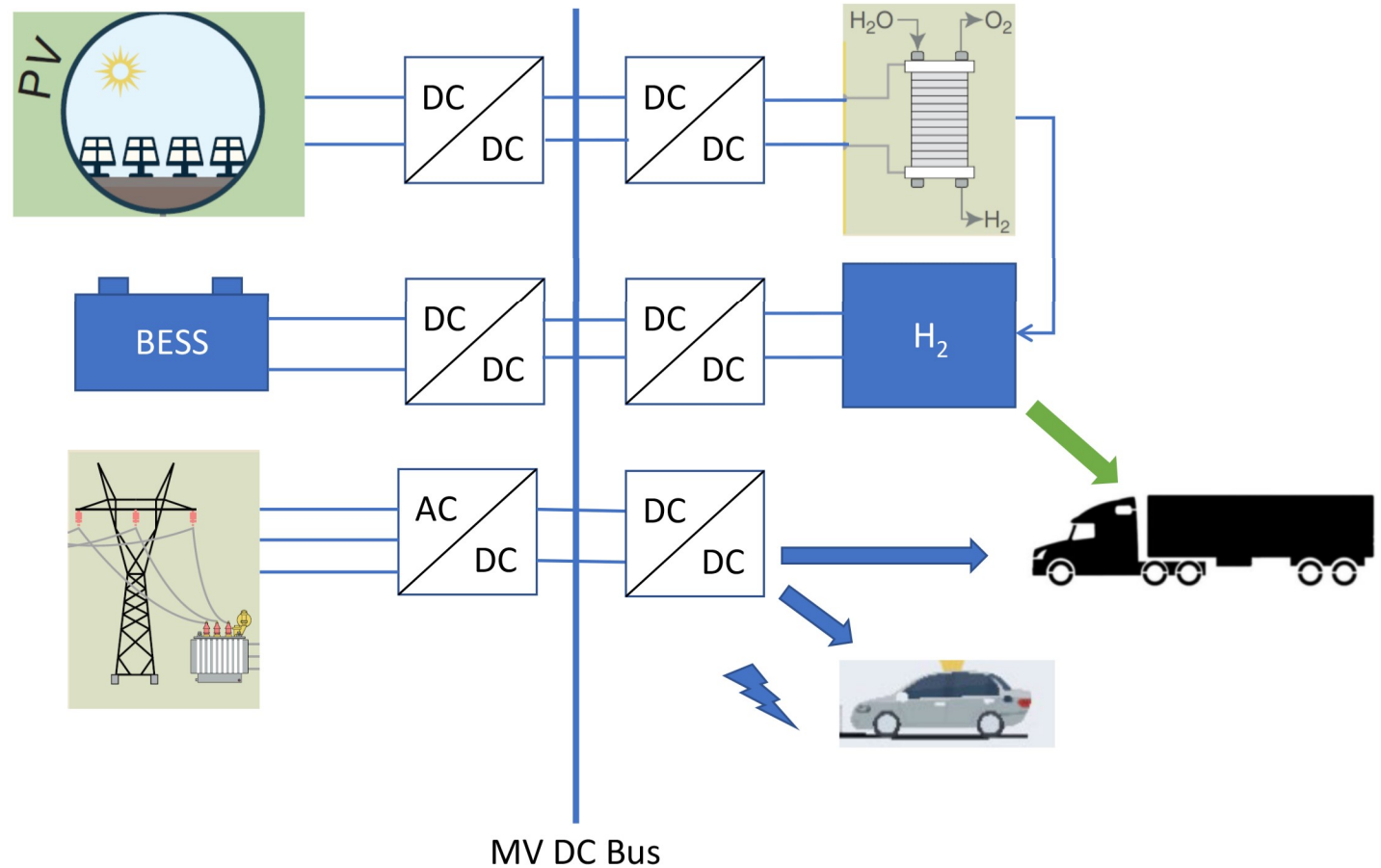
**Test Flight Feb. 20, 2023 on  
Ampaire Aircraft**

The Energy Council: Fuel Sources for APEG



## Electrification will evolve to include hydrogen:

- Hydrogen fuel cells will have a place => Can work with aircraft, marine, big trucking, off-road
- Makes less economic sense with passenger EVs, but is feasible (BEV uses 1/3 of energy – Martin Eberhard, Tesla Founder)
- Can work as bulk storage for grid
- Can play a role in methanol (CO<sub>2</sub> neutral)
- May be carried as ammonia

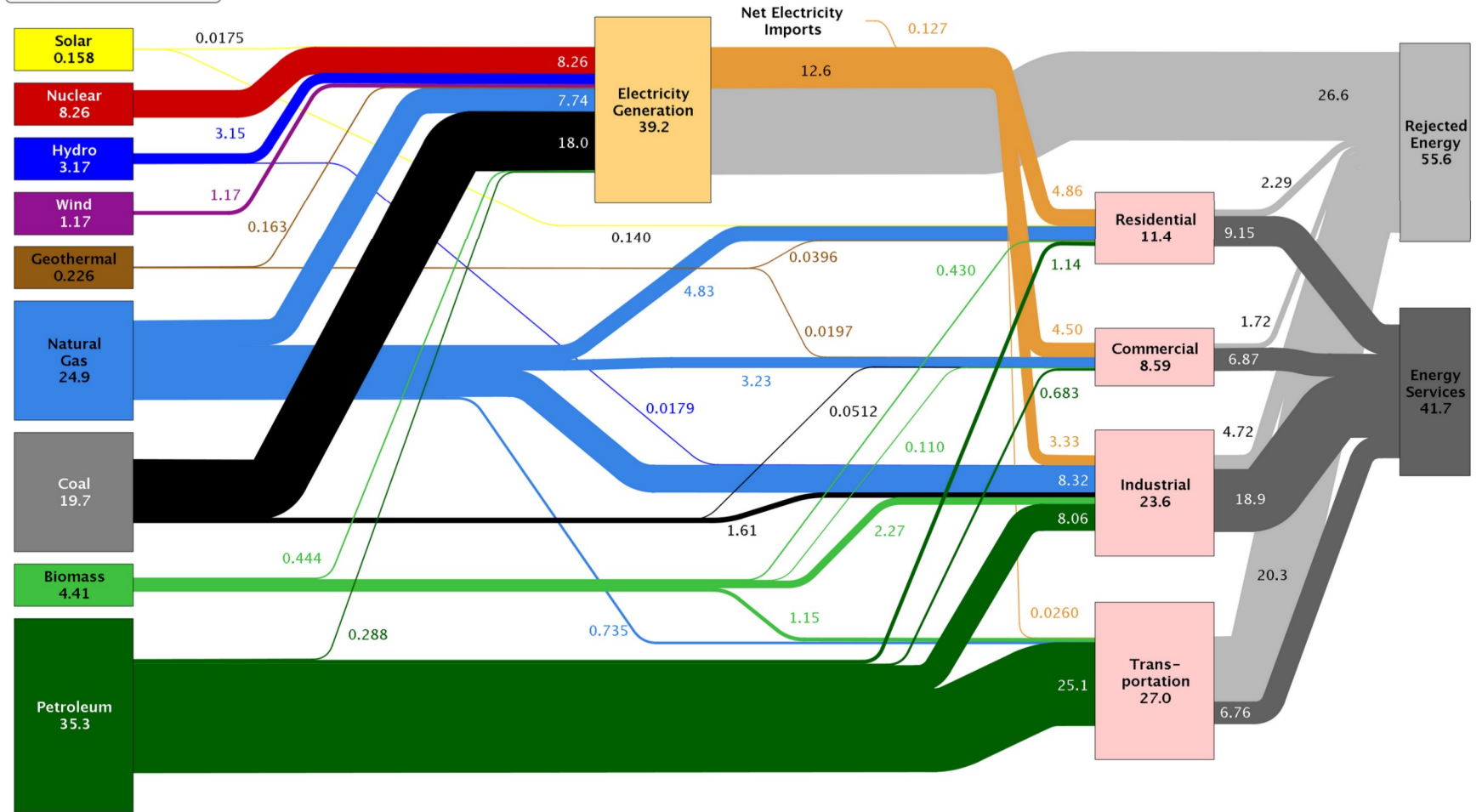


The Energy Council: Fuel Sources for APEG

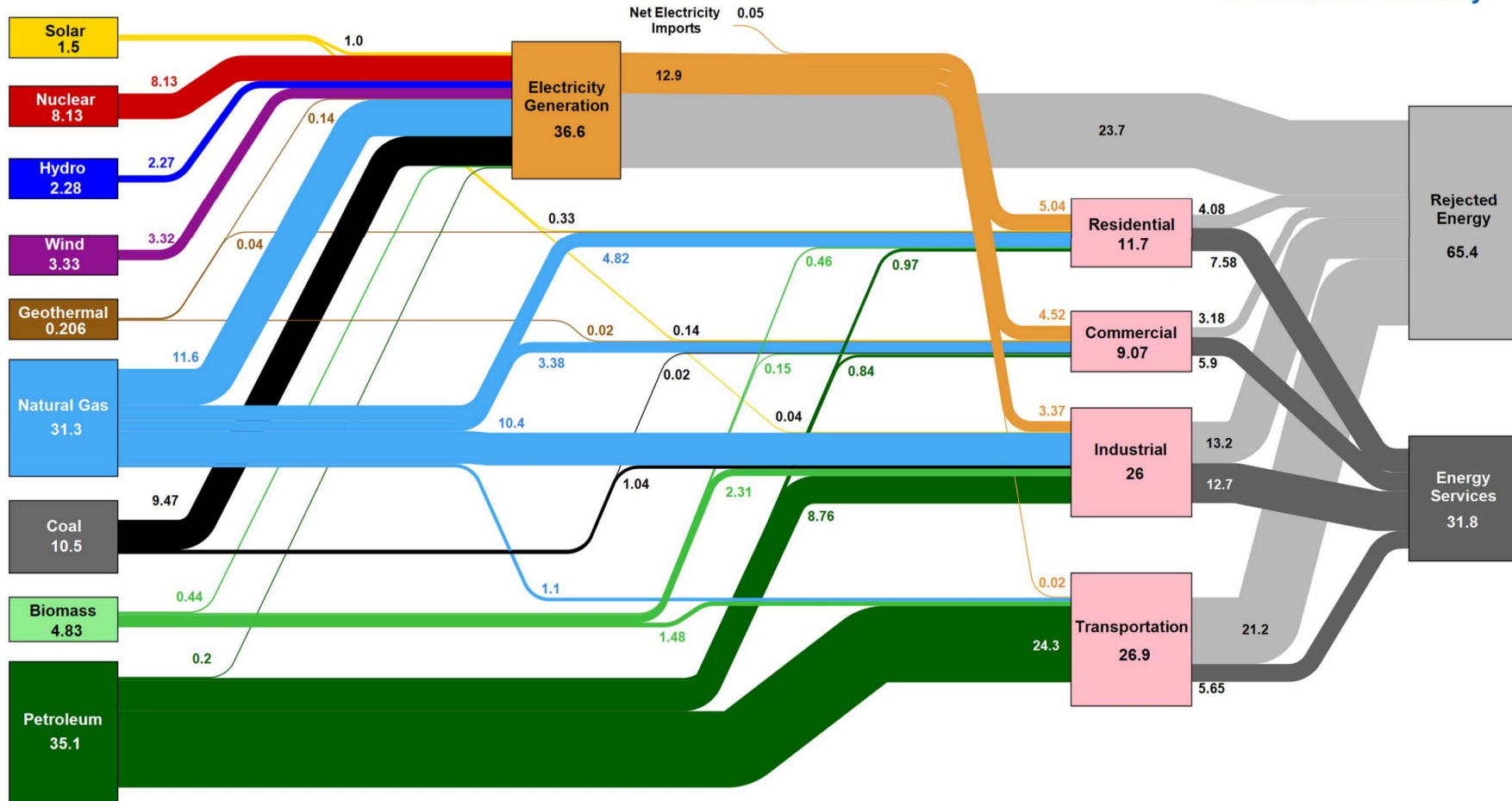


Estimated U.S. Energy Use in 2011: ~97.3 Quads

Energy 2011 United States



Estimated U.S. Energy Consumption in 2021: 97.3 Quads





# Switching from Fossil Fuels to 100% Renewable Energy Supply?

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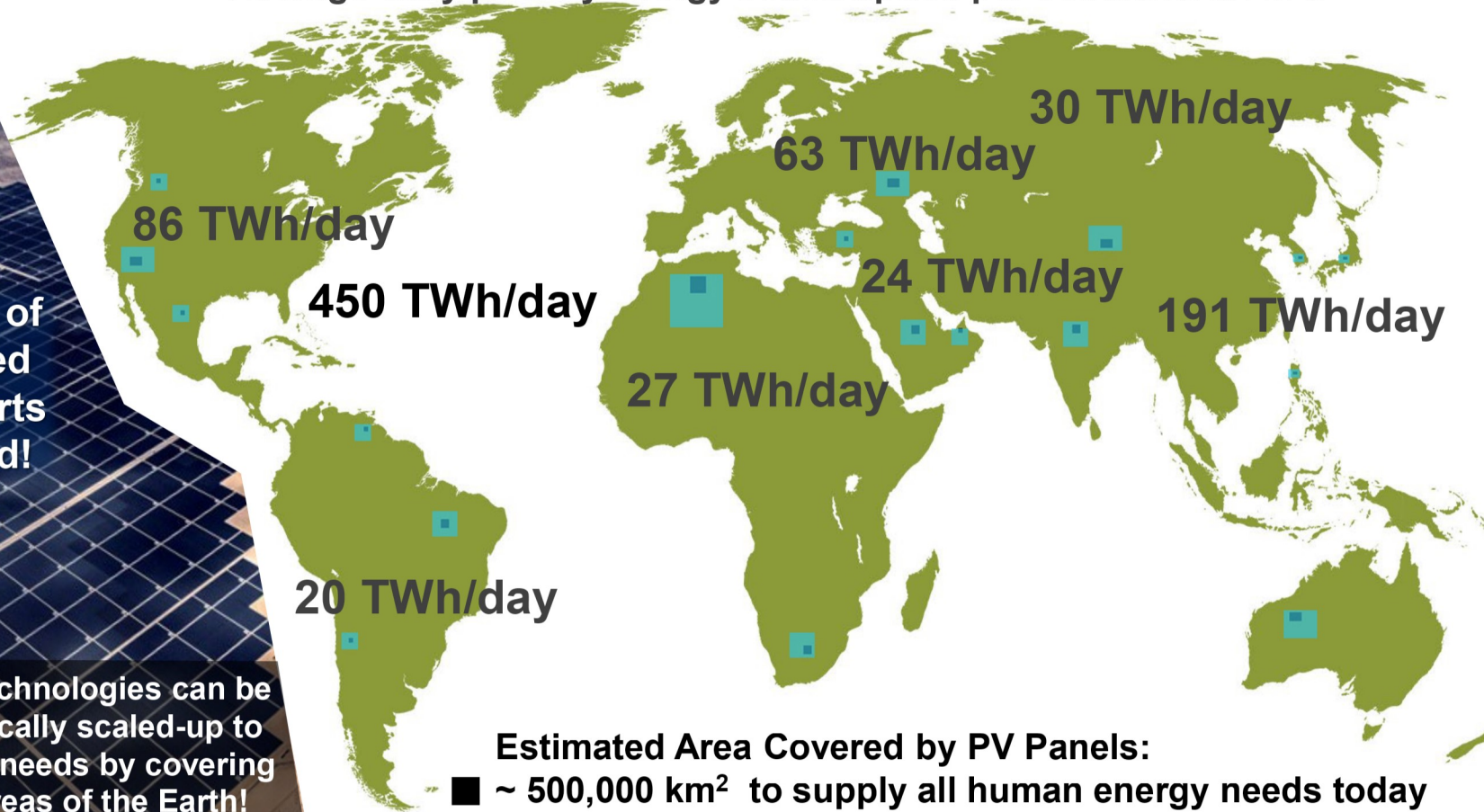
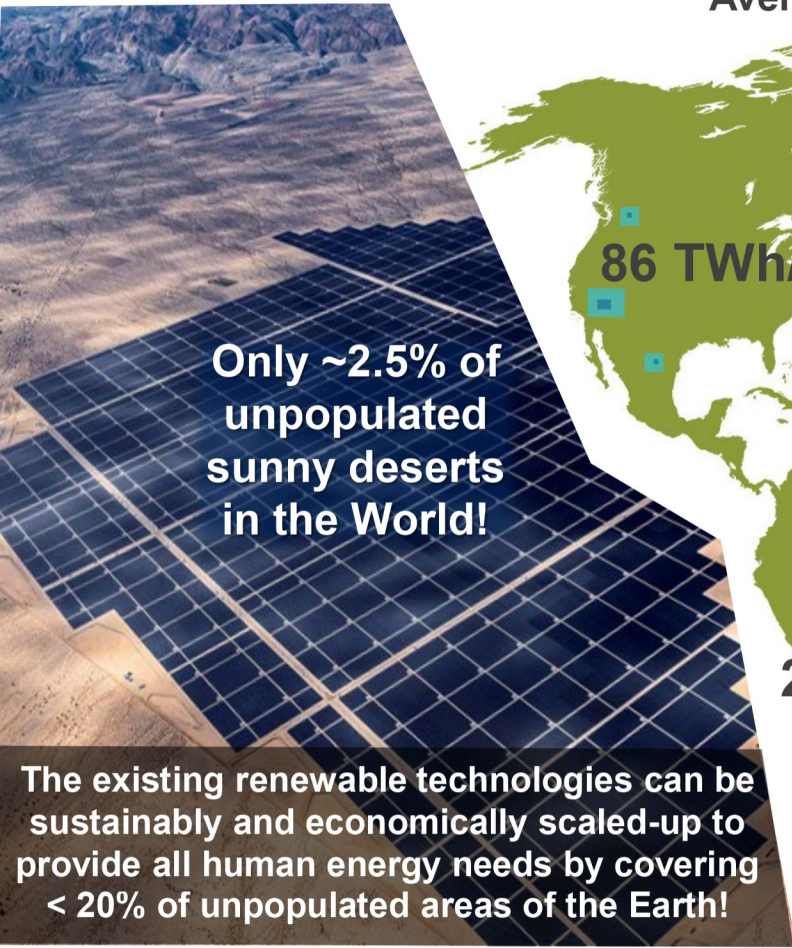
- Earth receives about 14,000 EJ of energy each day from Sun (Exa =  $10^{18}$ )
- About 10,000 times more than humankind's total primary energy consumption
- What is a Joule?

## **SUSTAINABLE ENERGY ABUNDANCE:**

**Total daily energy consumption of 10 billion humans, using per capita twice as much energy as an average American today, 30 years from now, will still be only about 0.1% of energy that is continuously received on Earth from the Sun each day!**

# Even if the World is Powered only by Solar

Average daily primary energy consumption per continent in 2020



Assumed insolation of 1000 W/m<sup>2</sup> for 5 h/day and efficiency of 18%

# Balancing Global Varying Generation with Varying Consumption

12h-average daytime power demand

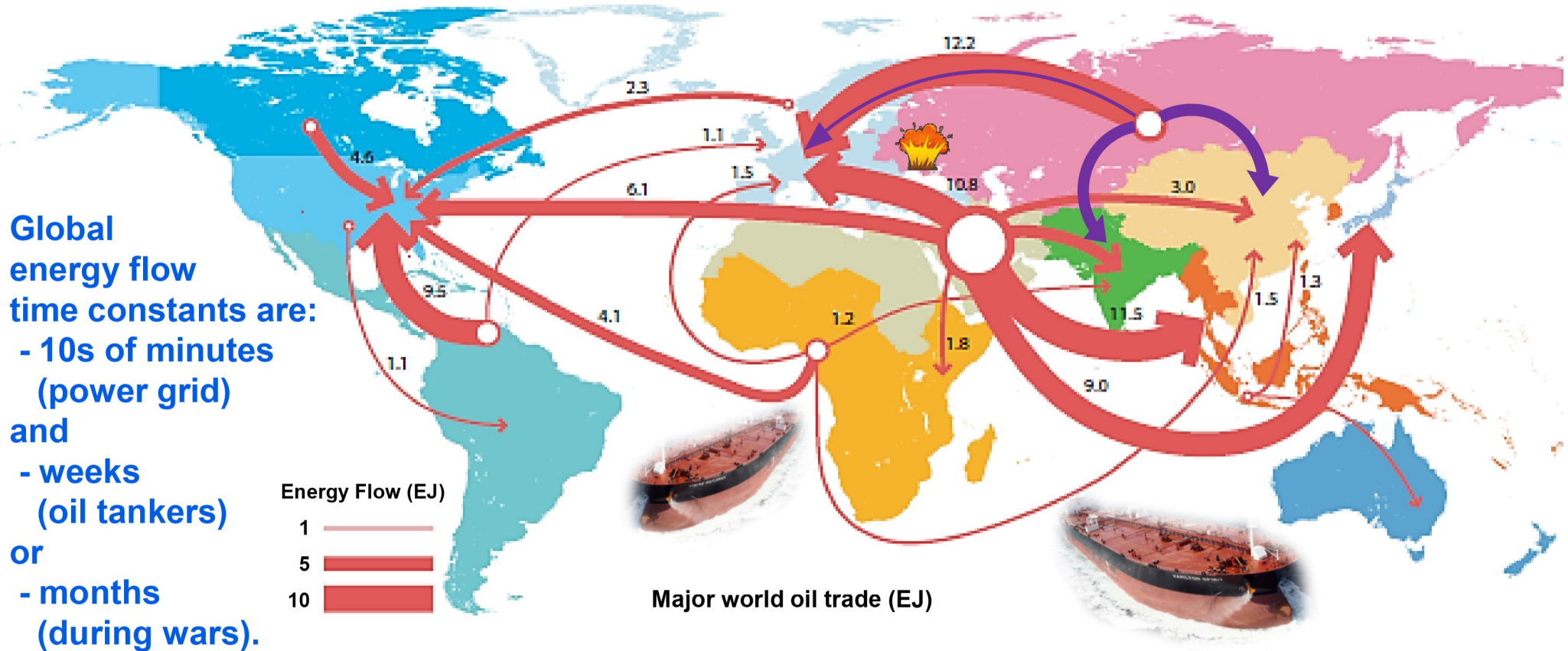
12h-average nighttime power demand



Sunny regions on earth can supply energy to areas under dark at sub-second time constants.

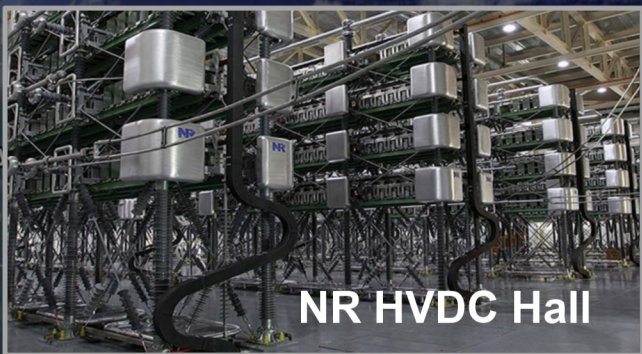
# Energy Supply Has Been Global Since 1900's

Over 1/3 of world primary energy is traded internationally!



**COVID-19 pandemic has taught us that global problems must use global solutions!**

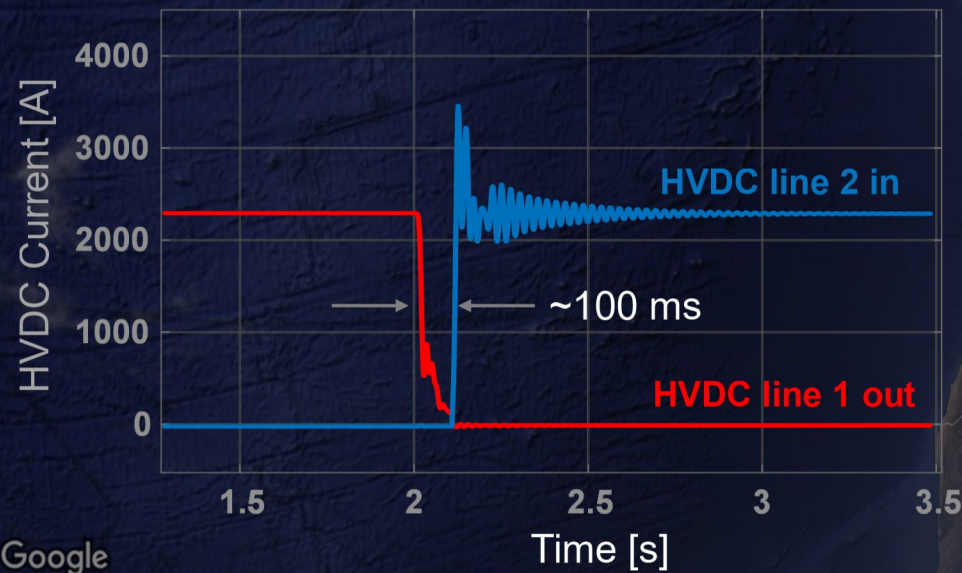
# Uninterruptible Intercontinental Energy Delivery



3 GW

$\pm 640$  kV

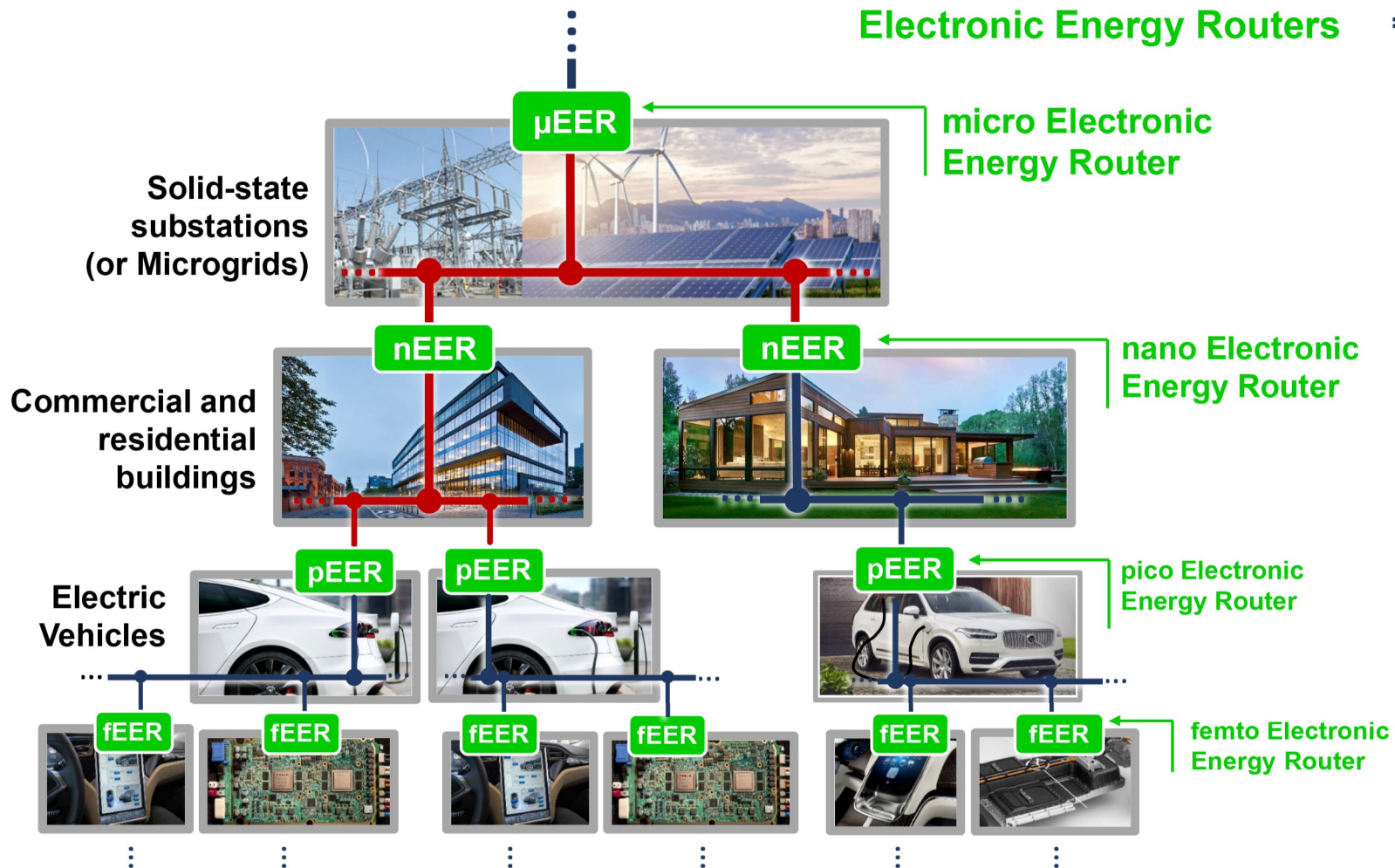
$\sim 4,000$  km



Google

# Intergrid

Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks

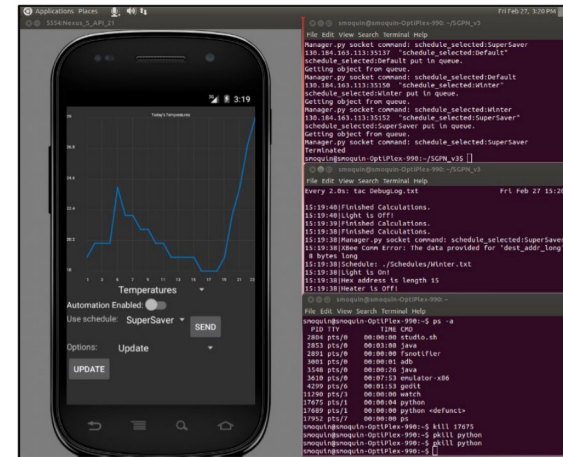
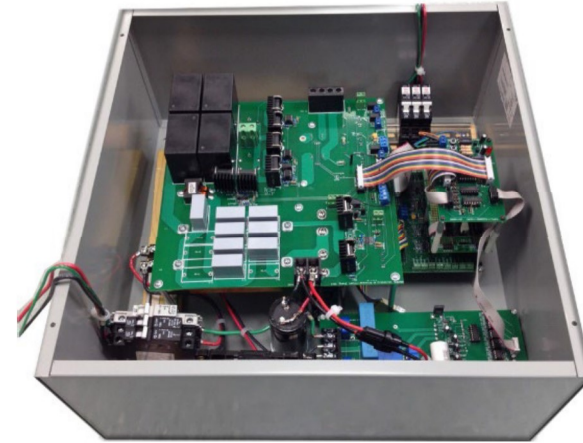


- = Bidirectional power converters for point-to-point energy flow control and integral protection;
- Every x-GRID is connected to a higher level by x-EER;
- Distributed energy generation and storage;
- Ability to operate in islanded mode;
- No thermo-mechanical switchgear;
- Step-up/down and isolation functions provided by the power converters (no low-frequency transformers);
- Extensive communication and control capabilities;
- **Standardized energy transfer & interconnection protocols are needed!**

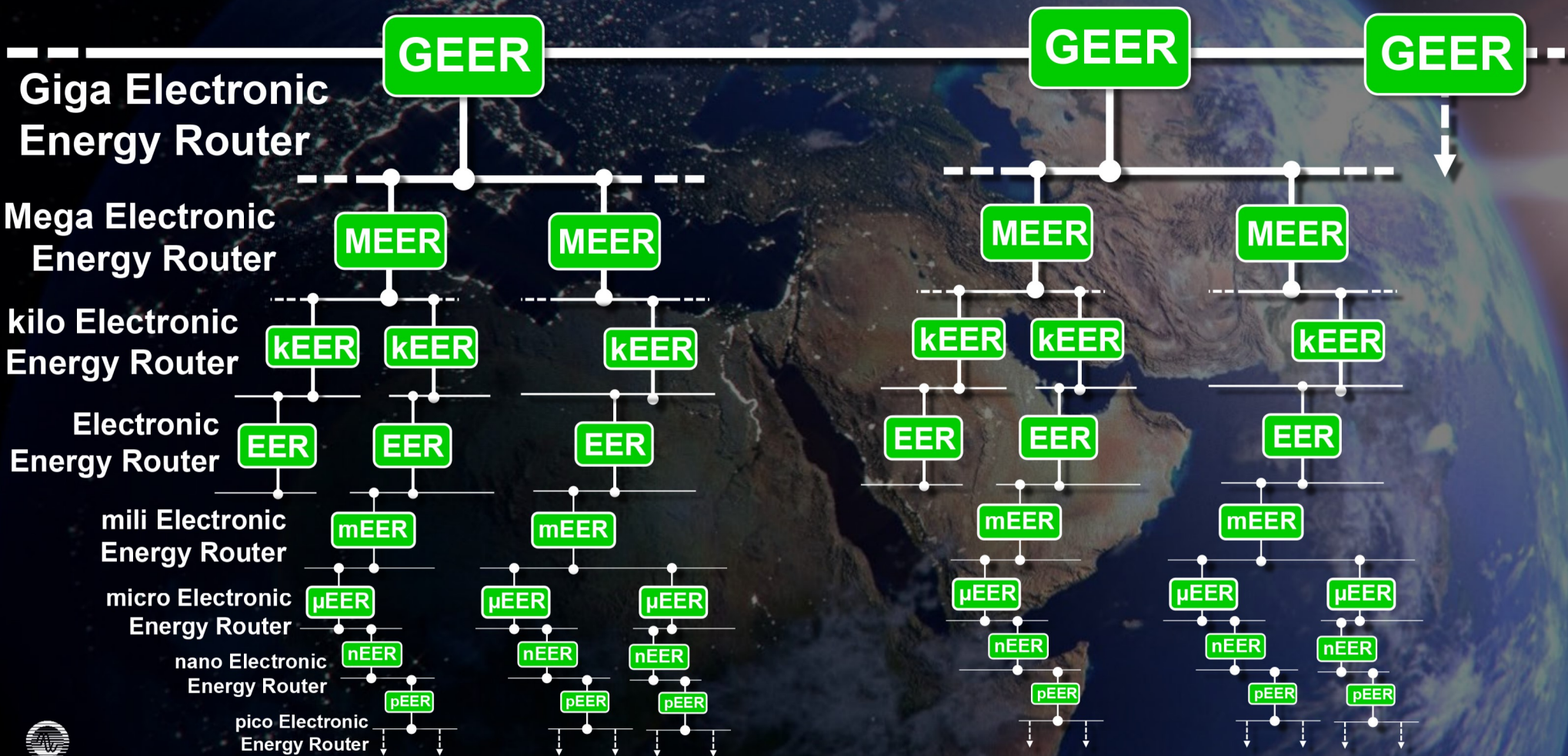
## Transformerless Battery Energy Storage Connection to 13.8 kV => MMC with advanced fault detection



## 5 kW Residential Power Router



# Global Intergrid





# **Global Intergrid for Sustainable Energy Abundance Starting with a Continental Intergrid Driven by Transportation**

**“Packets of electrical energy” can be sent at the speed of light between any two points on the Earth connected by electrical conductors!**

Global supplies of:

- silicon <sand)
  - aluminum <bauxite)
  - plastics <CO<sub>2</sub> capture, sea & air)
  - energy <Sun)
- are sufficient for this!

**We have the technologies and resources to do it, we  
just need the *will* !**

**A special thank you to my colleagues around the world, but particularly CPES @ Virginia Tech**

- **Managing energy supply, demand, and utilization is a global issue**
- **Electrical energy is growing evermore important in that management**
- **Power electronics is rapidly becoming the heart of many systems that drive decarbonization, electrification, and renewable energy**
- **Battery electrification has a place, hydrogen has a place, synthetic fuels have a place, renewables have a place => Thinking globally, but allocating locally is effective at determining solutions**
- **Evolving our existing grid infrastructure will be too slow for 2050, but needs to continue (vital)**
- **Creating new infrastructure that interties with existing, evolving infrastructure can get us there (requires more than government)**

# Tara Shaw

**From:** Alan Mantooth <mantooth@uark.edu>  
**Sent:** Sunday, September 17, 2023 11:15 AM  
**To:** Tara Shaw  
**Cc:** peter.green@nrel.gov; callen@misoenergy.org  
**Subject:** fun with presentations (Please forward)

**Importance:** High

**Follow Up Flag:** Follow up  
**Flag Status:** Flagged

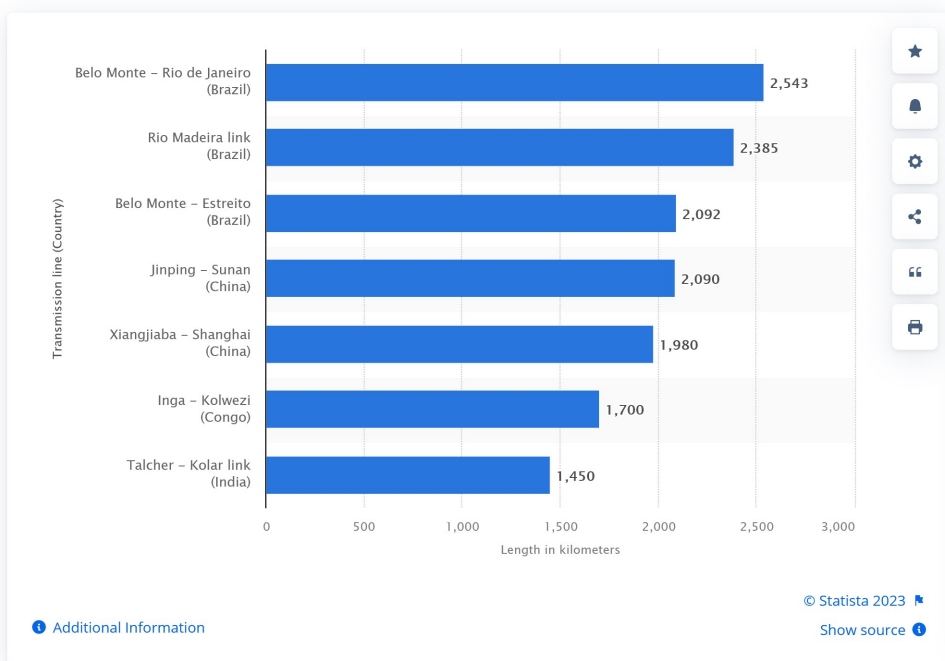
Hi Tara,

Hope you had a pleasant journey home. I have a fun “non-fact” to share with my audience on Saturday. I am known for sometimes putting little gotchas in my presentations to keep my students on their toes. I left one in the presentation and I want to set the record straight before others misquote anything... 😊. This one concerns the HVDC line from Brazil to Africa in one of my slides. That was a fairly elaborate simulation of such a line, and is not deployed. Why did I insert this? Certainly, not to make fun of anyone or otherwise alienate my audience. No, I did it to make a point that there really is no technological reason we cannot interconnect power like we have communications. And, there is living proof (see projects below).

Well, the world’s longest transmission line is the HVDC line in Brazil, so the story is CLOSE, but not subsea. (see <https://www.statista.com/statistics/1305820/longest-power-transmission-lines-worldwide/>) It is 2,543km (1580 miles). There are HVDC lines in Brazil, China, Congo, and India that are quite long. That is fact. The line I showed is a simulation of an intercontinental line that has been studied. All data is correct, but the line does not yet exist. However, others are proceeding!

## Longest power transmission lines worldwide as of 2020

(in kilometers)



There are subsea HVDC lines in S. Korea from their mainland to Jeju island (101 km or ~63 miles). That is fact. ([https://en.wikipedia.org/wiki/HVDC\\_Haenam%E2%80%93Cheju](https://en.wikipedia.org/wiki/HVDC_Haenam%E2%80%93Cheju)).

Just having a bit of fun, so I hope this doesn't lead someone to say that the entire presentation was all "Hokie BS"! 😊

Everything else was on the level. I just want to point out to folks that it really is important to verify some of the things you hear...because some things I heard Saturday morning seemed a bit off. They should be verified by our legislators and their staff. I'm happy to talk with any of the legislators or attendees at the Energy Council meeting should they wish to follow up.

Seriously, I hope I don't ruffle feathers with this little gotcha...we do have the technologies, and the resources, we just need the will. Please feel free to forward my e-mail in its entirety to the attendees. I know not all of them were able to stay, but at least they'll know they missed a fun time, right!

Best,  
Alan

Some other fun facts:

The longest subsea power cable is to run from Morocco to the UK.

<https://electrek.co/2022/04/21/the-worlds-longest-subsea-cable-will-send-clean-energy-from-morocco-to-the-uk/>.

Once complete it would be 2,361 miles long and carry 3.6 GW of power.

Currently, the longest subsea power cable connects the UK and Norway @ 450 miles long and an ultimate capacity of 1.4 GW (1400 MW). That will power 280,000 homes @ 5 kW each.

<https://www.cnn.com/2021/10/04/worlds-longest-under-sea-electricity-cable-begins-operations.html>

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